Frequency of extreme storms based on beach erosion at Northern Assateague Island, Maryland

By

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ABSTRACT

This paper examines morphologic response to storms at northern Assateague Island, MD. Time series of hindcast waves and water level were input to drive the SBEACH beach erosion and overwash numerical model to estimate beach response, ground-truthed by documentation and available evidence of storms that caused significant morphologic change at the site. The analysis proceeded through application of the generalized Pareto distribution, with tropical and extratropical storms treated as separate populations. Five storm-related parameters were examined and correlated with volume of beach erosion: peak surge, peak water level (surge plus tide), storm duration, and two new parameters called the integrated hydrograph and the integrated significant wave height, "integrated" referring to the product of time and water level or wave height above a threshold. Storm-induced erosion was found to be only weakly correlated or not correlated with the individual parameters of peak storm surge and peak water level. For tropical storms, erosion is strongly correlated with integrated wave height, and to a lesser extent with storm duration and integrated hydrograph, whereas for extratropical storms, erosion is found to be significantly correlated with the integrated hydrograph and to a lesser extent with integrated wave height and storm duration.

ADDITIONAL KEYWORDS: Beach, dune, storm surge, overwash, tropical storm, extratropical storm, waves, recurrence.

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Ocean-fronting beaches are becoming increasingly vulnerable to storms because of regional and local reductions in sediment supply and increases in density of development near the shore. Flooding, wave penetration, and erosion by storms can hold positive consequences for beaches as through creation and replenishment of habitat, and negative consequences as through damage to infrastructure. Global climate change suggests an increase in frequency and intensity of storms, demonstrated for hurricanes on the U.S. east coast by Komar and Allan (2008), in addition to a steady if not accelerated rate of sea level rise (National Research Council 1987; the Intergovernmental Panel on Climate — Bindoff *et al.* 2007). Flooding will damage buildings and other infrastructure through exposure to water and waves even if of short duration. In contrast, significant beach erosion by transport of sediment landward (overwash) and by seaward transport requires a longer duration. Erosion of dunes increases vulnerability to flooding and wave attack, and to other morphologic change such as scour along paved roads. As the duration of a storm continues and erosion persists, a barrier beach can be breached, altering the physical condition of the estuary and the beach adjacent to the breach.

Engineers and managers apply statistics of extreme values to determine the probability that the water level during a storm exceeds a certain elevation such as the height of a dike, seawall, or dune. Because of past emphasis on flooding as a cause of coastal damage, and because of the availability and reliability of water level data, there is a history of associating peak storm surge or peak total water level with the possibility of beach erosion. However, the shape of the storm hydrograph of total water level, involving time duration, is also a controlling factor for beach morphology change. Kriebel and Dean (1985) were perhaps the first to demonstrate the strong dependence of beach and dune erosion on storm duration. Through numerical simulation of beach and dune erosion with the SBEACH model (Larson and Kraus 1989), Larson and Kraus (1991) found that a short-duration hurricane with high surge and a long-duration extratropical storm with lower surge can produce similar magnitudes of dune and beach erosion. Depth-limited waves close to shore associated with both tropical and extratropical storms will have approximately the same height that depends primarily on total water level, so that higher water level of longer duration allows waves to attack higher on the beach or dune. Wave-induced set up and wave run-up also play a role in flooding and erosion, with longer duration storms allowing waves to erode the beaches during longer times of elevated water level (Kriebel and Dean 1985). Dolan and Davis (1992) introduced a power-type categorization of extratropical storms that included duration to classify storm damage. Burroughs and Shaffer (1997) discussed the role of duration for storm-induced coastal erosion, and Miller and

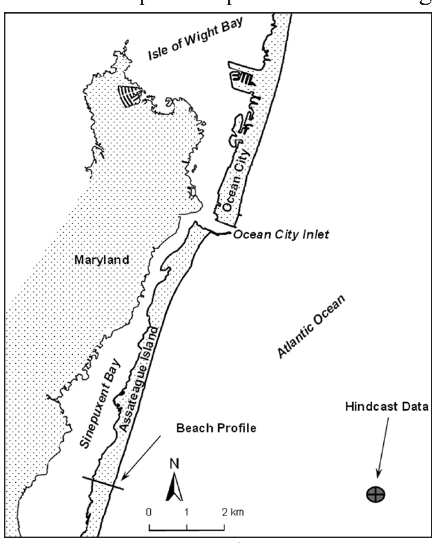

Figure 1. Location of study site.

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14. ABSTRACT
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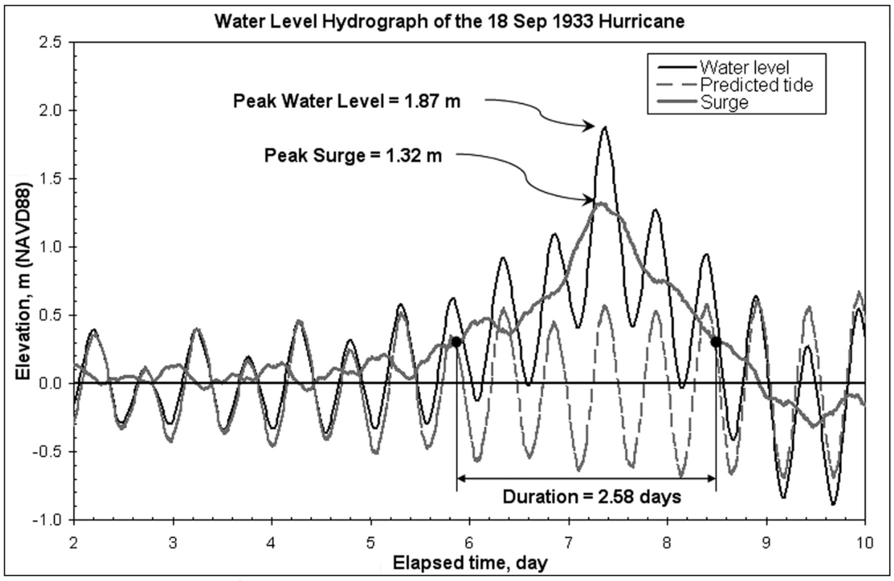
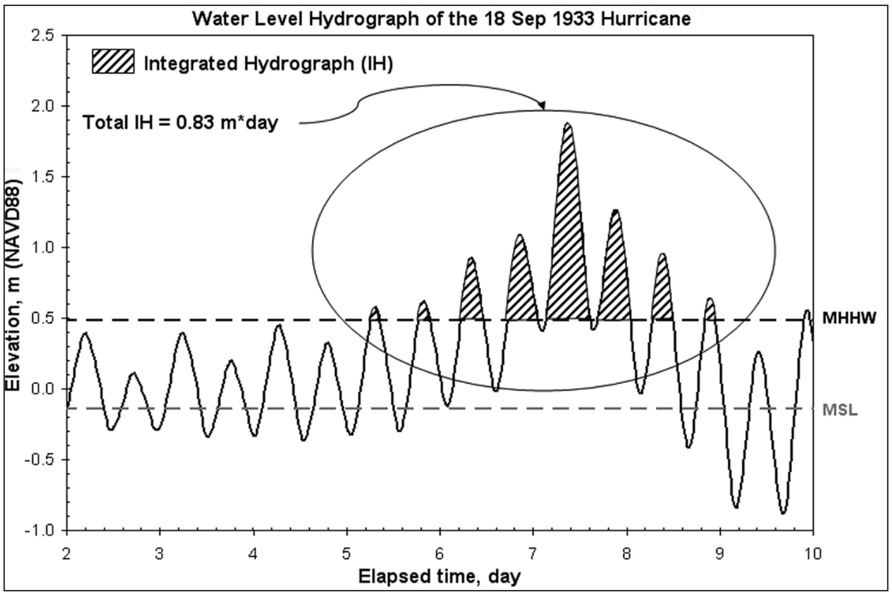


Figure 2 (above). Definition sketch illustrating peak total water level and peak surge.

Figure 3 (below). Definition sketch for the IH parameter.



Livermont (2008) defined a Storm Erosion Index for predicting shoreline recession through storm surge and wave height integrated over the duration of a storm. Sallenger (2000) introduced a storm impact scale involving four levels of net accretion or erosion, the last of which (Level 4) concerns complete inundation of a barrier island, indirectly bringing the concept of duration. Sallenger *et al.* (1999) applied the storm impact scale to examine morphologic response of northern Assateague Island to the January and February 1998 storms also examined here in a statistical approach. Thus, duration of super-elevated water level during storms is being recognized as a decisive factor for causing beach and dune erosion, although it has not yet entered pervasively in engineering design. Herrington and Miller (*this issue*) review other estimators of shore damage by storms.

This paper describes an investigation of frequency of occurrence of beach erosion, including overwash, at northern Assateague Island, MD, based on storm wave height and duration of super-elevated water level for both tropical and extratropical storms. Correlation of beach erosion and peak surge, peak total water level, storm duration, and two new parameters called the "integrated hydrograph," and "integrated significant wave height" are examined by means of a hindcast of major tropical and extratropical storms.

METHODOLOGY

Storm Database

The long-term storm hindcast analyzed in this study was performed by Oceanweather Inc., a consulting firm specializing in forecast and hindcast of meteorological and oceanographic information. The time-series was extracted from a long-term hindcast wind and wave spectra database named GROW_FINE-EC28km (Oceanweather 2007). GROW_FINE-EC28km is a nested high-resolution database within the Global Re-analysis of Ocean Wave (GROW) a global hindcast database covering the entire earth (Cox and Swail 2001). The wind fields were first developed based on re-analysis of historical meteorological data and then input to drive a calibrated spectral wave model and storm surge model. GROW_FINE-EC28km was developed for the U.S. east coast to address the intense tropical cyclones and winter storms with higher temporal and spatial resolution (~28 km). The hindcast time-series analyzed in this study was extracted from a point located 10 km offshore of northern Assateague Island, MD (Figure 1), at the 17-m isobath (NAVD88). The hindcast data set consists of time series of total water level and wave height, period, and direction at 30-min interval for significant tropical storms making landfall from 1924 to 2005 as Category 2 or greater by the Saffir-Simpson scale, and for significant extratropical storms (called "northeasters" locally) from 1957 to 2005. The resultant dataset documents 111 tropical storms and 35 extratropical storms.

The hindcast water level data sets were then carefully inspected by the authors and compared with historical data and documentation. Historical data includes the National Ocean Service (NOS) tide station at the Ocean City Fishing Pier, MD, tide station (1975-1991) and the Lewes, DE, tide station (1919-present). Inconsistencies, mostly related to the duration defining the simulated storms, were reported, and the particular hindcast was revised by Oceanweather Inc. for use in this study.

Study Site

Assateague Island, VA-MD, is located to the south and down-drift of Ocean City Inlet, MD (Figure 1). Ocean City Inlet formed on 13 August 1933 as a breach in the barrier island (Dean and Perlin 1977), and in 1934 and 1935 it was subsequently

stabilized with jetties by the U.S. Army Corps of Engineers. The northern end of Assateague Island forms the Assateague Island National Seashore of the National Park Service. Most of the northern end is low lying and has migrated inland more than an island width since Ocean City Inlet opened (Leatherman 1979). Erosion and overwash along the northern end of Assateague Island have led to breaching in the past, including a breach in 1956 that was closed by hydraulic dredge, and a breach in October 1961 followed by the March 1962 storm that was closed hydraulically in 1965 with dredged material (Dean and Perlin 1977). More recently, Assateague Island also breached in 1998 after two strong extratropical storms struck the shore within one week, as documented by Sallenger *et al.* (1999).

Storm Parameters

From the storm hindcast data, five parameters were selected to represent each storm: peak surge, peak water level (surge plus tide), storm duration, and two new parameters called the integrated hydrograph (IH) and integrated significant wave height (IHS). The predicted tide was removed from the total water level to give the storm surge, Figure 2. The height of the surge alone or peak water level, however, is not expected to be the only causative mechanism for overwash and breaching. To rank storms for statistical analysis of erosion and overwash, storm duration is an essential factor. Storm duration for this purpose at Assateague Island was defined as the amount of time the storm surge exceeded 0.3 m (Figure 2) to avoid ambiguities with the tide rising above Mean Higher High Water (MHHW) as discussed below. If the water level overtops the beach for only a few minutes, the associated sediment transport will be minimal; both longer storm duration and water level are required for significant erosion to occur. A parameter such as the integrated hydrograph combines water level height and duration by integrating the portion of the storm hydrograph above the tidal datum MHHW for the total duration of the storm (Figure 3). The IH parameter has the units of [L T] or meter-day and gives a unique value for each storm. High water level allows waves to penetrate deeper inland. Although depth limited, waves also contribute to the elevation of water level through wave set up and wave run-up, leading in particular to overwash

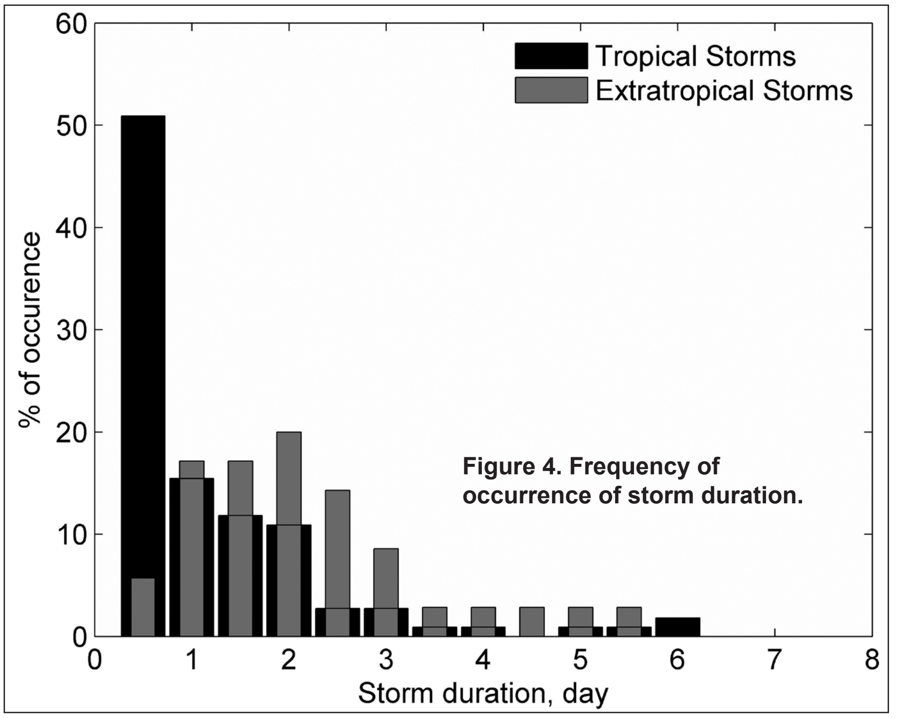


Figure 4. Frequency of occurrence of storm duration.

by wave run-up or by total inundation (Kraus and Wise 1993; Donnelly *et al.* 2006). Following the same concept as for the IH parameter, the IHS parameter is the significant wave height time series integrated over the duration of the storm and also has units of meter-day. Tidal datums were obtained from the former Ocean City Fishing Pier NOS tide gauge. At this location, MHHW and Mean Sea Level (MSL) are 0.48 m above and 0.14 m below NAVD88, respectively. For the IH parameter, the tide is included, as it contributes to total water level.

SBEACH

The SBEACH model (Larson and Kraus 1989) was selected to calculate beach and dune erosion, including overwash by either wave run-up or inundation (Donnelly *et al.* 2006), starting from the same initial beach and dune profile surveyed in April 2008. The same beach profile was used for all SBEACH simulations to provide an objective comparison base for all storms independently. Twenty-eight of the 111 tropical storms and 30 of the 35 extratropical storms in the hindcast were selected for input to drive SBEACH. The storm subsets include those having the largest IH and maximum water level. SBEACH was driven by time series of waves and water level from the hindcast of the storms in the subset, and it calculates wave set up and run-up based on the input forcing and calculated time-varying beach profile morphology (Larson and Kraus 1989). Wave setup and run-up add substantially to the water level that can, ultimately, transport sand. The total volume of sand eroded on the sub-aerial portion of the beach at the end of each storm was then correlated with the independent storm parameters of peak surge, total water level, storm duration, IH, and IHS.

Statistical Analysis of Extreme Storms

Statistical modeling of extreme values has the objective of determining the probability distribution function that best describes the largest or rarest values in a data set. Tropical and extratropical storms have different origins and meteorological conditions (see Herrington and Miller *this issue*), so they should be considered to belong to two distinct independent populations and treated separately. For example, the frequency distributions of duration of tropical and extratropical storms selected for analysis are plotted Figure 4. As is well known, tropical storms tend to have short duration, here showing a strong mode at 0.5 day and frequency distribution that decays strongly after two days, although long-duration tropical storms are rare but evident. In contrast, extratropical storms have a wider and more symmetric distribution with mode at two days.

Two approaches are commonly applied in extreme-value statistics, the Block-Maxima (BM) method and the Peaks-Over-Threshold (POT) method.

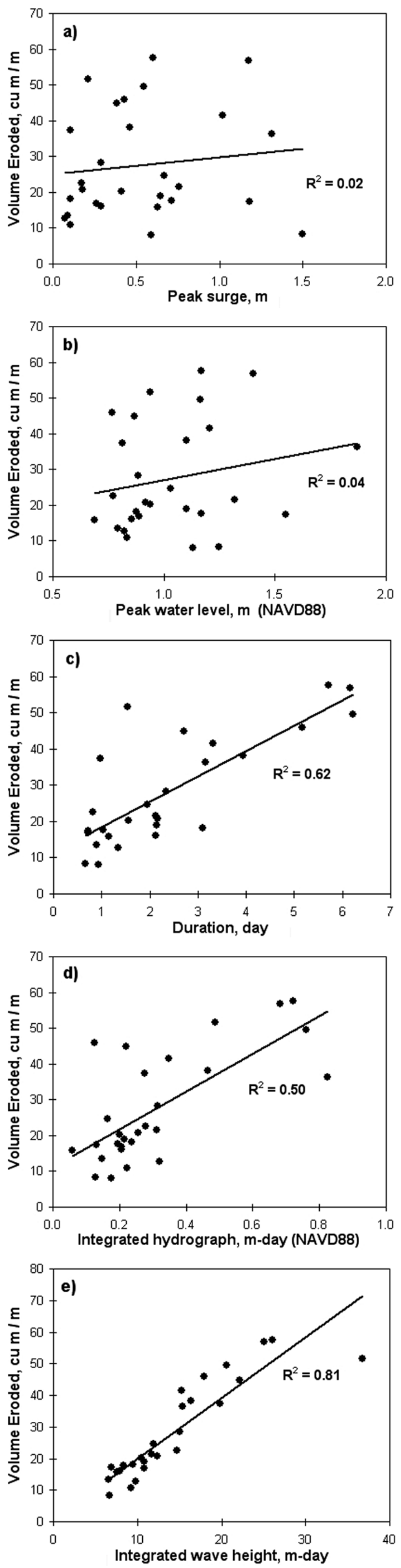


Figure 5. Tropical storms: Correlation analysis between the calculated volume of sand eroded and a) peak surge, b) peak water level, c) storm duration, d) integrated hydrograph, and e) integrated significant wave height.

Table 1. Return period (RP) of the top 10 tropical and extratropical storms ranked by peak surge.

	Tropical Storms			Extratropical Storms		
Rank	Date	Surge (m)	RP (year)	Date	Surge (m)	RP (year)
1	12 Sept. 1960	1.50	99	13 March 1993	1.06	20
2	18 Sept. 1933	1.32	53	5 Feb. 1998	1.06	20
3	27 Sept. 1985	1.18	34	8 Jan. 1996	1.04	16
4	16 Sept. 1967	1.18	34	29 March 1984	1.04	15
5	13 Aug. 1955	1.02	22	7 March 1962	1.01	12
6	16 Sept. 1999	0.92	16	4 Jan. 1992	0.97	9
7	25 Aug. 1933	0.76	11	3 March 1994	0.94	7
8	11 Sept. 1954	0.71	10	31 Oct. 1991	0.91	7
9	18 Sept. 2003	0.67	9	11 Dec. 1992	0.87	5
10	20 Sept. 1936	0.65	8	11 Feb. 1973	0.87	5

For the BM method, the data set is developed as the largest value in a certain block of time such as a year or a month. The resulting sample composed of yearly (or monthly) maxima is then fitted to a generalized extreme value distribution.

In this study, the statistical analysis of extreme storms leading to beach erosion is carried out using the POT method in which the sample is composed of all events exceeding a certain pre-selected high threshold. The events which exceed that threshold are then fit to a Generalized Pareto Distribution (GPD). The occurrence of major tropical and extratropical is not completely random, but is correlated to cyclic climatic phenomena such as the North Atlantic Oscillation (NAO) and El Niño-Southern Oscillation (ENSO) (Gulev *et al.* 2001; Jagger *et al.* 2002, among others). The POT method is therefore preferred over the BM method because it allows more complete coverage of available data by selecting all large events rather than a fixed number of events per year.

According to Fisher and Tippet (1928), there exist three types of extreme value distributions, Type I, II, and III, known as the Gumbel, Fréchet, and Weibull families, respectively. Each family has a scale σ and a shape parameter ξ, but has a different form of the tail (extreme value) behavior. A Weibull distribution ($\xi < 0$) has a finite maximum value, whereas the Gumbel ($\xi = 0$) and Frechet ($\xi > 0$) distributions are unbounded. These distributions are applicable only to regularly sampled data such as annual or monthly maxima.

The GPD combines the three families into a single 2- or 3-parameter distribution. This generality holds the advantages of not having to make either an a-priori or a-posteriori choice as to which one of the three families is the most appropriate for describing trends in a data set. The GPD is given by:

$$GPD\,(y) = 1 - (1 + \xi y / \sigma)^{-1/\xi} \qquad (1)$$

where $y = z - u$ = excess value above the threshold, z = parameter of interest, and u = high threshold; and σ and ξ = scale and shape parameters, respectively, for which Eq. (1) is to solved. The unknown parameters of the GPD distribution were estimated with the Maximum Likelihood Method using a subroutine provided in the Wave Analysis for Fatigue and Oceanography (WAFO) toolbox (WAFO-Group, 2000). Confidence intervals were determined for quantification of the uncertainties using the delta method. The general methodology followed is described in Coles (2001).

RESULTS

SBEACH was run to calculate the loss of sand on the sub-aerial beach and low berm along northern Assateague Island for the storm hindcast data set. The total volume of eroded sand was extracted and then correlated with the storm parameters of peak surge, peak water level, duration, IH, and IHS for tropical and for extratropical storms. The results are summarized in Figures 5 and 6, discussed next.

Figures 5 and 6 indicate that peak surge and peak water level are not correlated or only weakly correlated to the eroded volume of sand of the sub-aerial portion of the dune, with correlation coefficient of 0.02 and 0.04 respectively for tropical storms, and 0.17 and 0.33 respectively for extratropical storms.

Table 2. Return period (RP) of the top 10 tropical and extratropical storms ranked by peak water level (WL).

	Tropical Storms			Extratropical Storms		
Rank	Date	WL[a] (m)	RP (year)	Date	WL[a] (m)	RP (year)
1	18 Sept. 1933	1.87	155	7 March 1962	1.65	500+[b]
2	27 Sept. 1985	1.55	55	11 Dec. 1992	1.55	25
3	16 Sept. 1967	1.40	32	3 March 1994	1.44	9
4	25 Aug. 1933	1.32	24	28 Jan. 1998	1.44	9
5	12 Sept. 1960	1.25	18	17 Feb. 2003	1.40	8
6	16 Sept. 1999	1.22	16	4 Jan. 1992	1.40	7
7	13 Aug. 1955	1.21	15	5 Feb. 1998	1.39	7
8	11 Sept. 1954	1.17	13	31 Oct. 1991	1.38	7
9	31 Aug. 1999	1.17	13	7 Feb. 1978	1.36	6
10	20 Sept. 1961	1.16	12	29 March 1984	1.35	6

a) Water level is referenced to NAVD88.
b) Because of the shape of the return period curve (Figure8a), a small difference in the hindcast water level may greatly change the return period.

Storm duration is moderately correlated with erosion with correlation coefficients of 0.62 and 0.72 for tropical and extratropical storms, respectively. The two integrated parameters, IH and IHS, are the best predictors of eroded volume of beach, with correlation coefficients of 0.5 and 0.81, respectively, for tropical storms and 0.83 and 0.74 for extratropical storms, respectively. Because tropical storms are of relatively short duration, the IH parameter does not give strong correlation as compared to extratropical storms. Similarly, integrated wave height is interpreted to have strong correlation with eroded volume for tropical storms because duration is not as variable as for extratropical storms.

Peak Surge

Figure 7 illustrates the fit of the GPD to the data with the peak surge for the ranking. The return periods of the top 10 tropical and extratropical and storms estimated from the fitted GPD are tabulated in Table 1. Hurricane Donna (September 1960), which ranked number one, is not remembered as a high-surge event at Assateague because the peak surge occurred at low tide. The September 1960 hurricane is an example of the role of total water level (including tide) and not just surge in defining a flooding condition. The Great Hurricane of 1933 (September 1933) ranks second based upon peak surge, but is the highest recorded water level because it occurred at high tide. The Ash Wednesday storm (March 1962) that breached Assateague Island ranks fifth, whereas the March 1993 storm (Rank 1) produced only minor erosion despite the hurricane-force wind and amount of snowfall. The outcome of ranking storms by catastrophic morphology change (beach and dune erosion, overwash, breaching) based upon peak surge is sometimes contradictory and not in accord with experience of erosion at the site.

Peak Water Level

Figure 8 illustrates the fit of the GPD to the data based upon peak water level (including tide) for the ranking. The return periods of the top 10 tropical and extratropical storms are tabulated in Table 2.

Ranking of the storms by peak water level is more in accord with observation where acknowledged high-erosional impact storms such as those of March 1962 and September 1933 rank first. Hurricane Gloria (September 1985) ranks second with a return period of 55 years. This storm is well remembered because severe erosion occurred, causing extensive damage to the Ocean City boardwalk. However, Hurricane Gloria was of short duration, lasting 1.5 tidal cycles. Erosion calculated with SBEACH at Assateague Island is relatively small at 17 cu m/m compared to 58 cu m/m for Hurricane Floyd (August 1999). Observed severe damage along Ocean City, MD, was probably due to the fact that the beaches in front of the boardwalk were relatively narrow at that time.

Storm Duration

Figure 9 illustrates the fit of the GPD to the data using storm duration for ranking. The return periods of the top

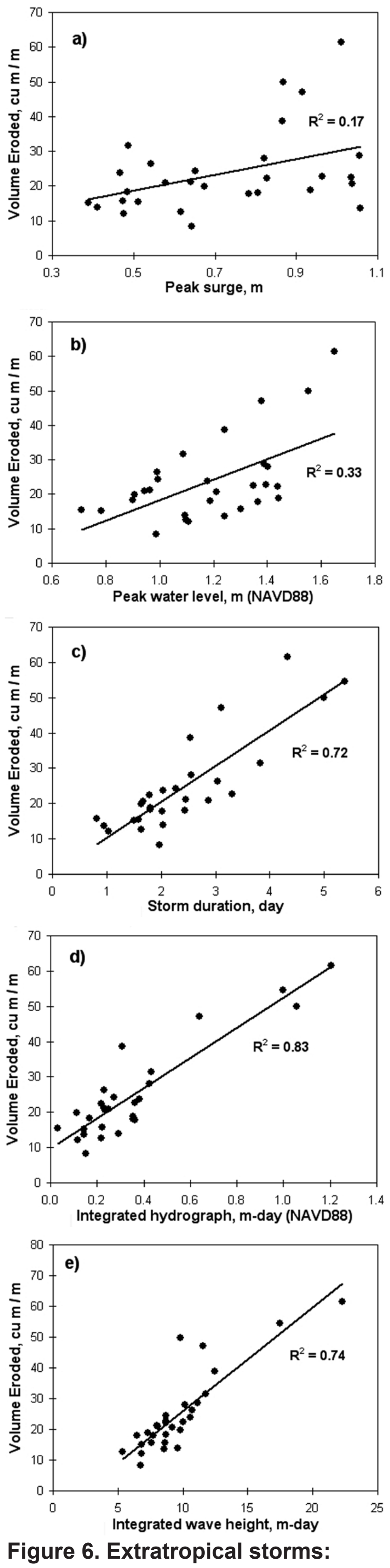
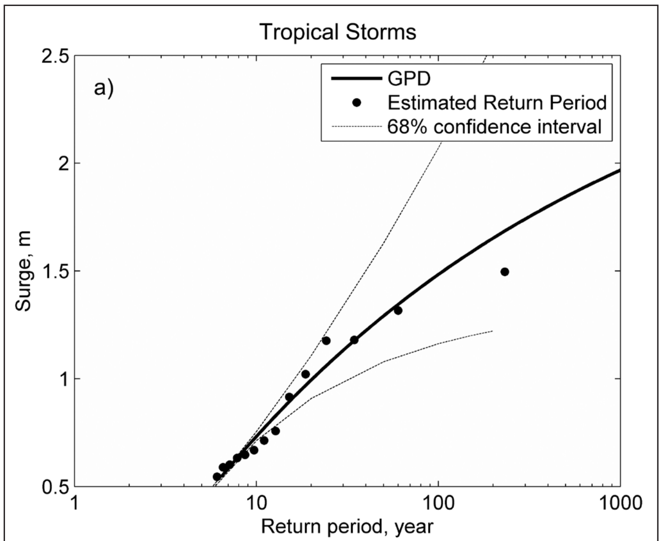


Figure 6. Extratropical storms: Correlation between calculated volume of sand eroded and a) peak surge, b) peak water level, c) storm duration, d) integrated hydrograph, and e) integrated significant wave height.



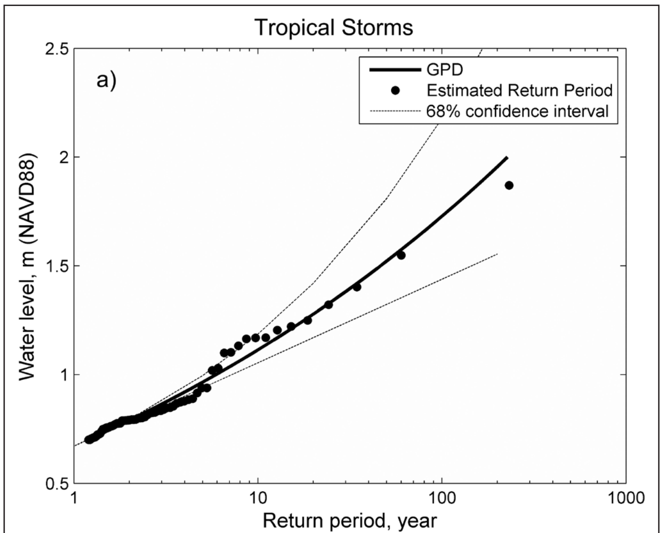
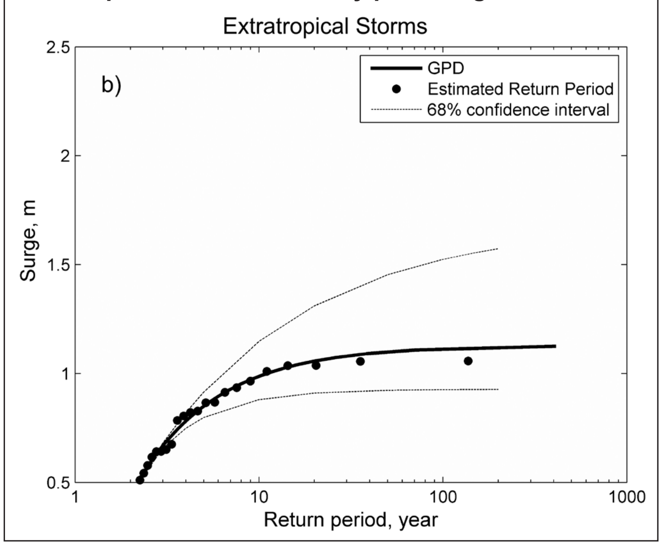
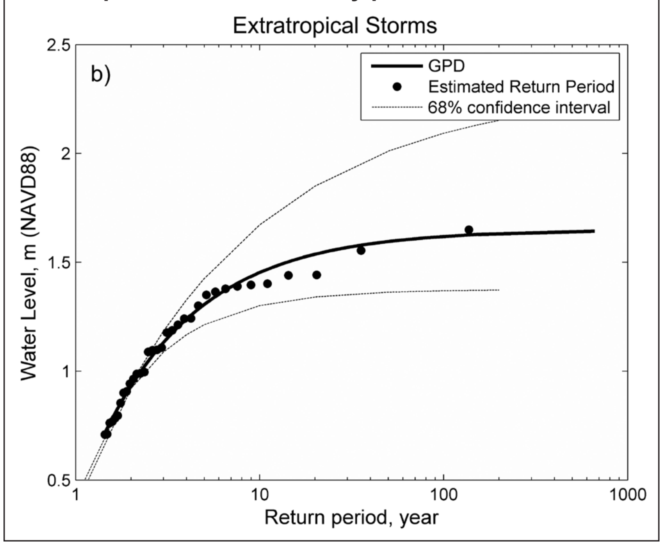


Figure 7. Return periods of a) tropical storms, and b) extratropical storms ranked by peak surge.

Figure 8. Return periods of a) tropical storms, and b) extratropical storms ranked by peak total water level.





10 tropical and extratropical storms are tabulated in Table 3.

The January 1998 storm, further discussed in the next section, denotes the combined January 1998 and February 1998 storms and ranks first for extratropical storms with a return period of 119 years. The December 1992 storm, ranking second, persisted over nine tidal cycles, caused strong overwash over northern Assateague Island. The duration parameter highlights the three most historically damaging extratropical storms at Assateague Island although not in intuitive order.

Hurricane Esther (September 1961) and tropical storm Doria (September 1967) had unusual trajectories, hovering in the Atlantic Ocean for several days and producing long durations of high water. Erosion calculated with SBEACH was large for both storms. Assateague Island was breached following Esther, and both storms caused damage to the Ocean City seawall and boardwalk. They have a return period of 85 and 82 years, respectively, based on storm duration.

Integrated Hydrograph (IH)

Figure 10 illustrates the fit of the GPD to the data using IH parameter for storm ranking. The return periods of the top 10 tropical and extratropical storms are tabulated in Table 4.

In the winter of 1998, two medium-sized extratropical storms struck the Assateague Island shore within a week of each other (28 January and 5 February). By the time the second storm arrived, the already severely overwashed Assateague Island had breached. The time between the two storms was too short to allow the beach to recover after the first storm. The two storms, taken separately, have return periods of 9 and 7 years based upon peak water level. As opposed to the other storm parameters, the IH parameter of each storm can be added to better represent the strength of the impact. The combined IH of the 28 January and 5 February 1998 extratropical storms has a value of 1.0 m-day, ranking it the third-largest extratropical storm with a return period of 46 years. The 1998 storms falls slightly behind the second-ranked storm is the December 1992, which overwashed Assateague Island. The first-ranked storm is the Ash Wednesday storm (March 1962) and has a return period of 89 years based on the IH parameter. The March 1962 storm is commonly considered to have modified northern Assateague Island the greatest, and it is also the storm that produced the most erosion, calculated by SBEACH to be a volume of 61 cu m/m. The tropical storms have smaller IH values by about 30% as compared to the extratropical storms.

Integrated wave height (IHS)

Figure 11 illustrates the fit of the GPD

to the data using the IHS parameter for ranking. The return periods of the top 10 tropical and extratropical storms are tabulated in Table 5. Ranking second for tropical storms are Hurricane Floyd (August 1999), whose eye passed over Ocean City. Floyd is the tropical storm having the largest calculated erosion at 58 cu m/m slightly more than the September 1967 storm (57 cu m/m) and the September 1971 storm (52 cu m/m). IHS is the only parameter that successfully identified these three tropical storms as producing the most calculated erosion, although not in order. The September 1971 Hurricane Ginger had a small storm surge, but attacked the shore with large waves for 20 days. This is the longest-duration storm in the record at 29 days. The surge is small, however, and significant wave height exceeded 1 m for 20 days, but with a maximum of only 2.3 m.

The fit to the GPD of the extratropical storm for the IHS parameter produced a large confidence interval (Figure 11b). The two top-ranked storms deviate considerably from the rest of the sample, skewing the tail of the distribution. Therefore, resultant return periods should be viewed with caution, and further quantitative refinement will have to await a longer hindcast time interval. However, the overall ranking of the storms provides the satisfying result that the top two are the March 1962 and the combined January-February 1998 storms, both of which breached the island.

Table 3. Return period (RP) of the top 10 tropical and extratropical storms ranked by storm duration.

	Tropical Storms			Extratropical Storms		
Rank	Date	Duration (day)	RP (year)	Date	Duration (day)	RP (year)
1	21 Sept. 1961	6.23	85	28 Jan. 1998	5.37	119
2	16 Sept. 1967	6.17	82	11 Dec. 1992	5.00	61
3	31 Aug. 1999	5.71	63	7 March 1962	4.33	24
4	19 Aug. 1995	5.17	45	17 Jan. 1980	3.83	14
5	23 Sept. 1964	3.94	20	4 Jan. 1992	3.31	8
6	13 Aug. 1955	3.31	13	31 Oct. 1991	3.10	7
7	16 Sept. 1933	3.17	11	22 March 1973	3.04	7
8	26 July 1926	3.10	11	21 March 1958	2.87	6
9	1 Aug. 1990	2.85	9	17 Feb. 2003	2.56	4
10	22 Oct. 1963	2.71	8	11 Feb. 1973	2.54	4

Table 4. Return period (RP) of the top 10 tropical and extratropical storms ranked by the IH parameter.

	Tropical Storms			Extratropical Storms		
Rank	Date	IH (m•day)	RP (year)	Date	IH (m•day)	RP (year)
1	18 Sept. 1933	0.83	80	7 March 1962	1.21	89
2	20 Sept. 1961	0.76	63	11 Dec. 1992	1.06	55
3	31 Aug. 1999	0.72	54	28 Jan. 1998	1.00	46
4	16 Sept. 1967	0.68	46	31 Oct. 1991	0.64	14
5	13 Aug. 1955	0.49	20	17 Jan. 1980	0.43	6
6	4 Oct. 1971	0.49	20	17 Feb. 2003	0.42	6
7	23 Sept. 1964	0.47	18	1 Dec. 1974	0.38	5
8	14 Aug. 1939	0.32	8	7 Feb. 1978	0.36	5
9	23 Aug. 1949	0.32	8	4 Jan. 1992	0.36	5
10	20 Sept. 2004	0.31	8	3 March 1994	0.35	5

Table 5. Return period (RP) of the top 10 tropical and extratropical storms ranked by the IHS parameter.

	Tropical Storms			Extratropical Storms		
Rank	Date	IHS (m•day)	RP (year)	Date	IHS (m•day)	RP (year)
1	30 Sept. 1971	36.7	175	7 March 1962	22.3	134
2	31 Aug. 1999	26.1	48	28 Jan. 1998	19.9	81
3	16 Sept. 1967	25.0	42	11 Feb. 1973	12.5	12
4	22 Oct. 1963	22.2	28	17 Jan. 1980	11.8	9
5	21 Sept. 1961	20.6	21	22 March 1973	10.7	7
6	16 Sept. 2005	19.8	19	14 Nov. 1995	10.6	6
7	19 Aug. 1995	17.9	14	1 Dec. 1974	10.6	6
8	23 Sept. 1964	16.4	11	17 Feb. 2003	10.2	5
9	16 Sept. 1933	15.4	9	29 March 1984	10.0	5
10	13 Aug. 1955	15.2	9	4 Feb. 1961	9.8	5

APPLICATON TO THE 11-14 NOVEMBER 2009 STORM

While this paper was being prepared, the extratropical storm of 11-14 November 2009 struck the mid-Atlantic coast of the United States, causing erosion from Virginia to Rhode Island (Watts *this issue*). Grosskopf and Bass (*this issue*) document this storm and its consequences for the federal shore-protection project at Ocean City, MD, which is co-sponsored by the state of Maryland. Consequences of the December 1992 storm at Ocean City are discussed in a special issue of *Shore & Beach* (Kraus 1993), in which Kraus and Wise (1993) compare storm ranking based on individual parameters such as peak surge, maximum wave height, and maximum wave period to those formulated in the General Design Memorandum (GDM) for the project (U.S. Army Corps of Engineers 1989). The GDM incorporated storm duration in combination with other storm parameters, and it treats surge as the major storm parameter corresponding to consideration of damage by flooding and wave attack, and not solely by erosion.

Under the present unified GPD methodology and database for extratropical storms, Tables 1-5 indicates a peak surge of 1.41 m (NAVD88) for a very long return period (RP) that is difficult to quantify under Figure 7b; a peak water level of 1.6 m (NAVD88) giving 500-year RP (comparable to the March 1962 northeaster); storm duration of 3.85 days, giving a 15-year RP; IH of 0.96 m-day,

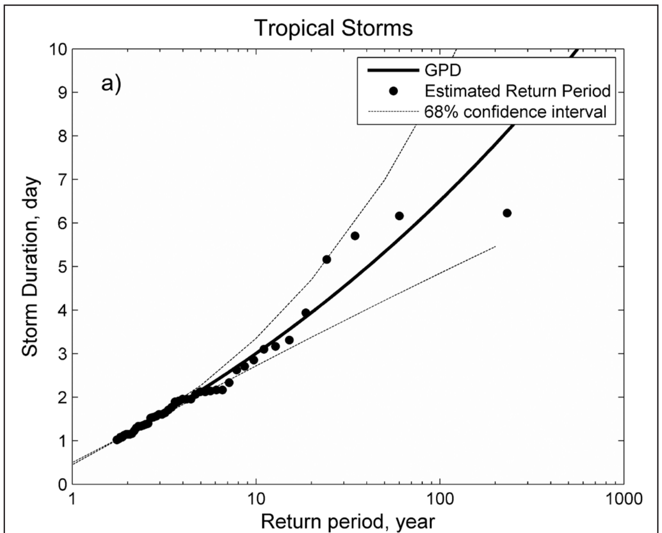
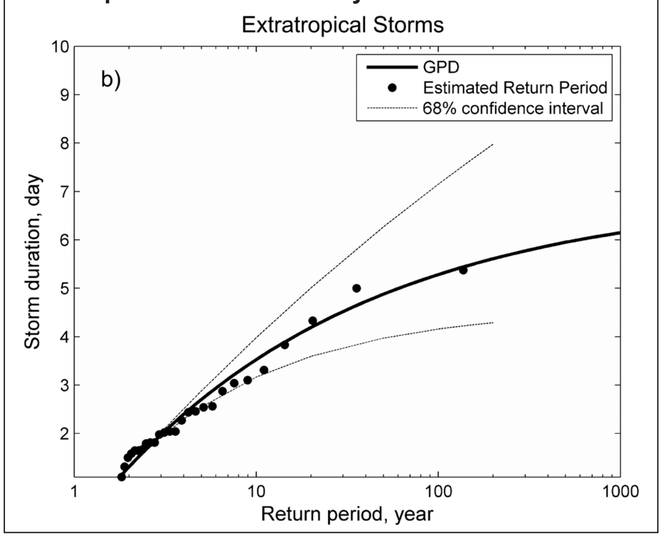


Figure 9. Return periods of a) tropical storms, and b) extratropical storms ranked by storm duration.



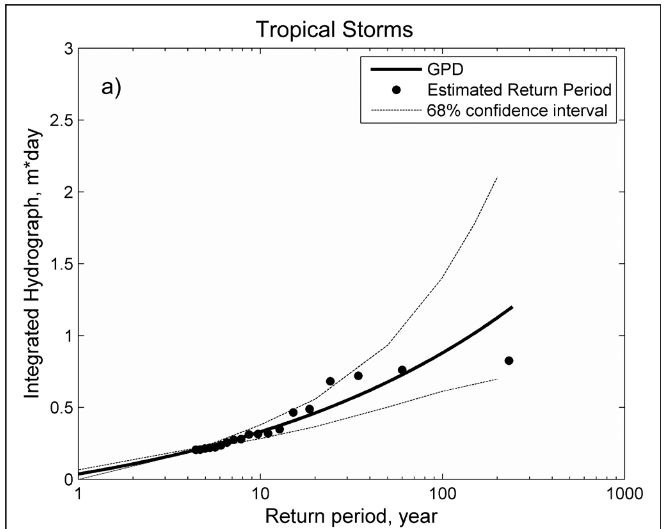
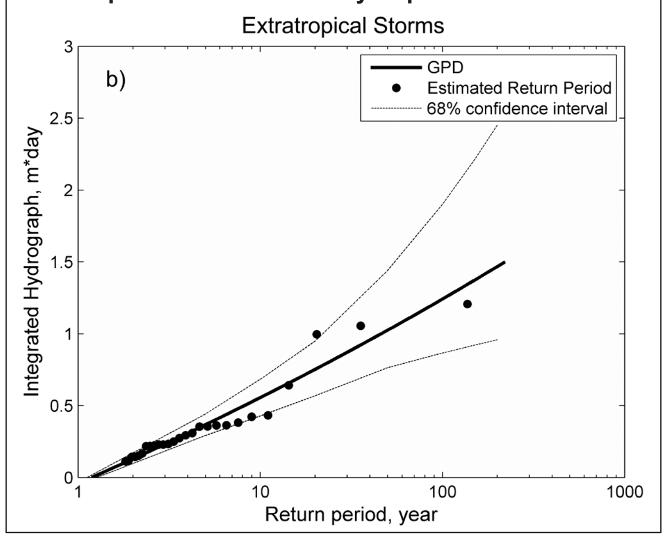


Figure 10. Return periods of a) tropical storms, and b) extratropical storms ranked by IH parameter.



corresponding to a RP of 45 years, and an IHS of 20.5 m-day, giving a RP of about 90 years. For this discussion, it is assumed that SBEACH would give a similar magnitude of response of the dune and beach at Ocean City. Previous work (Kraus and Wise 1993) demonstrated that SBEACH reproduced storm-induced erosion and overwash for the December 1992 storm along several beach profiles. Based upon the strongest correlation of the IH and IHS parameters with eroded beach volume (Figure 6) for extratropical storms, it is concluded that with regard to beach erosion, the Nov 2009 storm can be assigned a RP between 45 and 90 years. Such a value is considered realistic, but must be viewed as hypothetical because of the assumption of equivalence in SBEACH results for the two sites.

CONCLUSIONS

Storm-related damage along a coast can occur by extreme wind speed, flooding, wave attack on the upper beach and infrastructure, and by erosion. This paper has principally investigated erosion through correlation of calculated storm-induced beach erosion on northern Assateague Island, MD, with storm parameters in two distinct populations for tropical storms and extratropical storms. The approach taken was through the Generalized Pareto Distribution, in which the extreme is determined by the data and not through a-priori selection of the distribution.

For predicting erosion by storms, traditional storm parameters of peak surge and peak total water level were found to be unreliable. The occurrence of significant erosion requires sufficient duration of elevated water level; therefore, three other parameters – duration of the storm, integrated hydrograph (IH), and integrated significant wave height (IHS) were investigated. For tropical storms, which had a mode of a half-day for the data set analyzed, beach erosion was best correlated with IHS, which is reasonable because the durations of most tropical storms is about the same. For extratropical storms, which had a broad distribution in duration, beach erosion was best correlated with IH, storm duration, and IHS.

For both storm tropical and extratropical storms, parameters related to storm duration were found to be strongly correlated with erosion. Therefore, it appears warranted to continue examining these correlations and methodologies similar to that presented in this paper for predicting erosional response for longer databases and other sites. Also, it is clear that extratropical storms along the central and northeast coast of the United States can cause comparable or greater damage than tropical storms (hurricanes).

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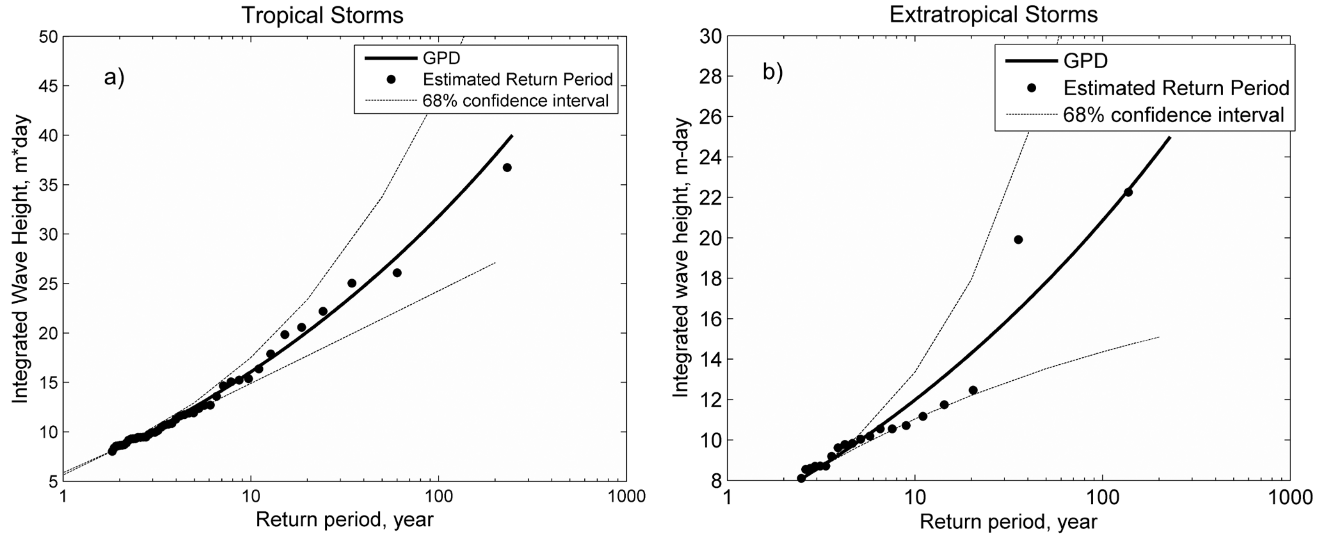

Figure 11. Return period of a) tropical storms, and b) extratropical storms ranked by IHS parameter.

Corps of Engineers, Baltimore District; by William G. Grosskopf of Offshore and Coastal Technologies Inc.; by Lynn M. Bocamazo and Jeffrey A. Gebert of the New York District and Philadelphia District, respectively, of the U.S. Army Corps of Engineers; and by Dr. Julie Dean Rosati of the U.S. Army Engineer Research and Development Center. Observations by Assateague Island National Seashore Park Service staff (Carl Zimmerman, Courtney Schupp) were relied on for interpretation of morphologic response of Assateague Island to recent major storms. This work was performed under the Geomorphic Evolution work unit of the Coastal Inlets Research Program and through study support by the Baltimore District in the Ocean City Inlet, MD, Bypassing and Backpassing Project. Permission was granted by Headquarters, U.S. Army Corps of Engineers, to publish this information.

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